Measurements of the natural plasma flow during the precursor of TCABR density limit disruptions

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Introduction

Magnetic islands are known to degrade confinement of energy and particles in tokamak plasmas. They are also present in the precursor of density limit disruptions being observed until the onset of the energy quench of the disruption. The subject of the effect of plasma flow on tearing mode stability has been studied both theoretically [1] and experimentally [2]. However the experimental work has focused on plasmas with Neutral Beam Injection (NBI), which adds high momentum to both the plasma and the island, deviating them from their natural velocities. It is important to know the plasma/island rotation behavior without NBI, not just to know their natural values but because future large tokamaks, like ITER, are expected to have low plasma rotation due to both large plasma inertia and low applied torque. In this work we will show experimental values of the ion velocity and the magnetic island velocity measured in TCABR ohmic plasmas, without NBI, and during the precursor of a density limit disruption. In this way it was possible to compare the natural plasma velocity with the island velocity. The ion velocity was inferred from Doppler spectroscopy of the impurity lines of CVI. Details of this diagnostic system and an error analysis of the measured signal can be found in [3]. With the present set up, the toroidal velocity can be measured with time resolution equivalent to 600 Hz and precision somewhat better than 5 km/s.

Plasma parameters and experimental conditions

The events described here were observed in several TCABR hydrogen plasmas with the following typical range of parameters, $60\,\text{kA} \leq I_p \leq 80\,\text{kA}$, $B_\phi = 1.06$ T, $a = 0.18$ m, $R_0 = 0.61$ m, and $q_a \approx 3.5$. The electron density was ramped up, to provoke a density limit disruption. During the plasma current flat top a magnetic island with $m/n = 2/1$, where m and n are the poloidal and toroidal mode numbers, exhibited fast growth to saturation with its amplitude remaining constant for approximately 20 milliseconds before the plasma disrupted (see plasma #30026 in Fig. 1 (d)). This type of behavior, commonly observed in tokamaks, has the peculiar feature

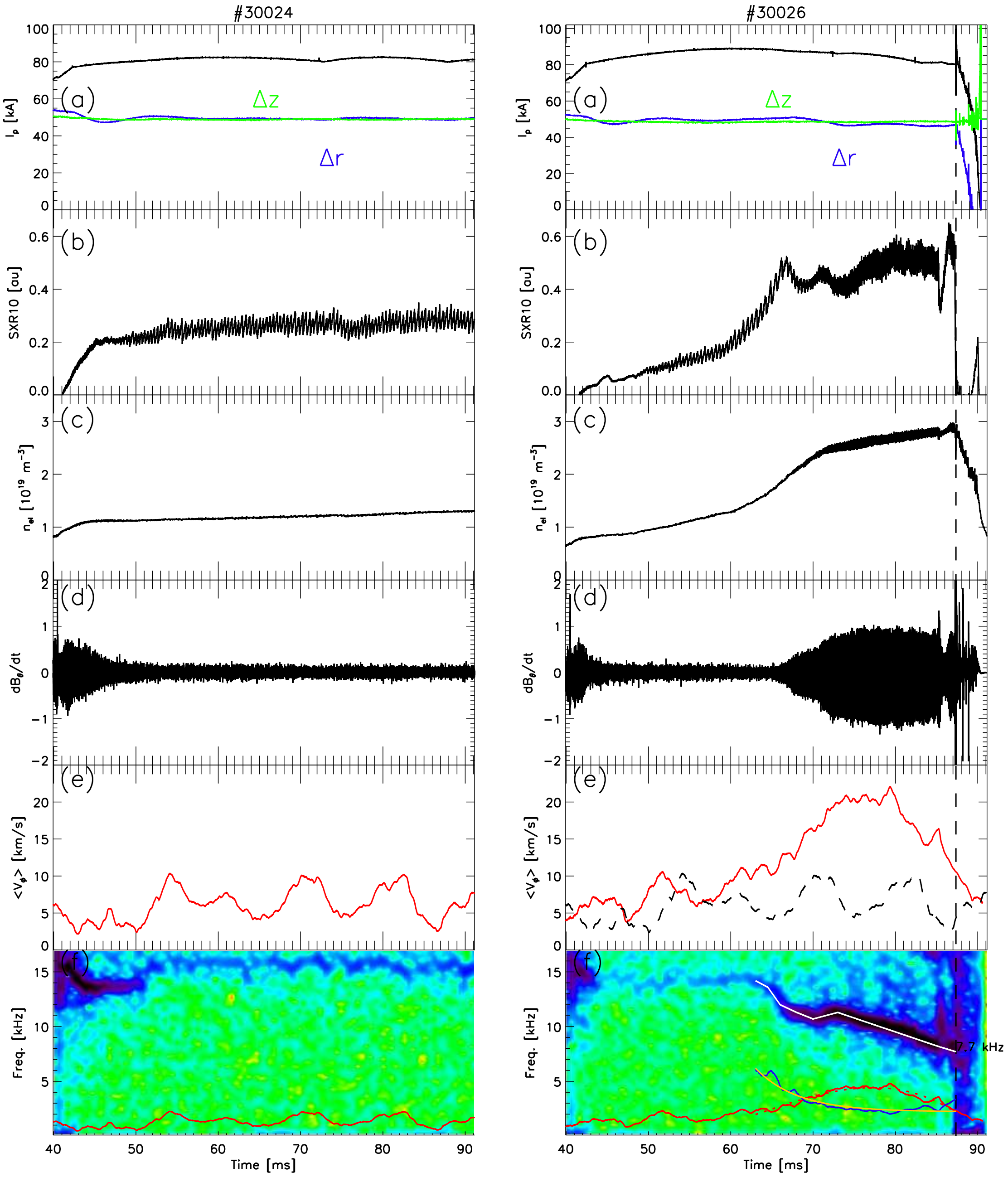

Figure 1: (a) plasma current, I_p, radial, Δr and vertical, Δz displacements of the magnetic axis, (b) SXR central chord, (c) central electron density, n_e at $r = 0.5$ cm, (d) dB_θ/dt, (e) intrinsic average toroidal rotation velocity $< v_\phi >$ measured at $r = 12$ cm, (f) spectrogram of dB_θ/dt with the toroidal rotation shown at (e) expressed in Hz (red line). For plasma #30026 is also shown the ratio f_{island}/f_ϕ (blue line).

in which the mode stays with very large and constant amplitude during several milliseconds until the disruption occurs. This clearly points out that the mode amplitude *per si* is not a sufficient condition to trigger the disruption. As is also well known, in parallel with the amplitude evolution is observed a reduction in the mode rotation frequency (Fig. 1 (f)) mainly due to the interaction of the mode with the metallic wall. For the plasmas in this study the disruptions occurred when the island rotation was $7.5 \leq f_{MHD} \leq 7.9$ kHz. Each tokamak has its characteristic range of frequencies for which disruptions occur. In large ones disruptions occur when the mode stops rotating and locks to the wall. It is not known why the disruption occurs at these frequencies, however the fact that it does reveals that somehow rotation can be part of a disruption trigger. We will show new input to this question, where it was found that at the disruption the plasma and the island toroidal angular acceleration, α tend to the same value.

TCABR operates with the plasma current opposite to the toroidal magnetic field B_ϕ and the intrinsic toroidal rotation is in the direction of B_ϕ or in counter current direction. The plasma toroidal velocity, v_ϕ was measured at the radial position of the mode's rational surface, $q = 2$ at $r_{island} = 12$ cm. The measurements were done in a plasma with a $2/1$ island (see #30026 in Fig.1(e)) and in a plasma without an island (see #30024 in Fig.1(e)). The plasma toroidal rotation is also displayed in Fig.1(d) in units of Hz for better comparison with the island rotation frequency.

Island and plasma rotation

As the mode amplitude suddenly increases its rotation frequency drops from approximately 14 kHz to 11 kHz. The plasma toroidal rotation frequency, that is in the same direction as that of the island, increases slightly from 2.3 kHz to 2.6 kHz. So while the plasma experiences a small acceleration the island is decelerating. The island rotation keep's on decelerating until reaching the lowest rotation speed of ≈ 7.7 kHz at the disruption.

However the plasma will only accelerate for about more 10 ms until it's rotation frequency reaches the maximum value of 4.5 kHz (or 20.9 km/s), at around 76 ms. From this time on the plasma will also decelerate. In Fig.2 (a) are plotted both the plasma and island toroidal angular acceleration. These curves were obtained from the derivative of a 3rd order polynomial fit of the velocity measurements also shown Fig.2 (b). The vertical dotted line indicates the time of the disruption. At this time the plasma is rotating at 2.3 kHz which is about three times smaller than the rotation of the magnetic island.

For comparison is also shown in Fig.1 discharge #30024 without magnetic island. For this discharge all parameters were kept the same as for #30026, with the exception of the density that was maintained constant at about 1.1×10^{19} m^{-3}. The plasma toroidal rotation also measured at $r = 12$ cm is observed to evolve at around 5 km/s throughout the discharge. This is in sharp contrast with the behavior in plasma #30026 where $< v_\phi >$ reaches a maximum value of

20 km/s, when the island amplitude was saturated, which is four times higher than the speed without island. We are still analyzing the behavior of the plasma poloidal rotation that is more difficult to interpret because considering the predictions of neoclassical theory, the main ions poloidal velocity can be quite smaller than that of the impurities, in particular close to the plasma edge [4]. Even so it is clear that the island rotates at a quite different velocity from the plasma with the island apparently being able to drag the plasma. This indicates the island slips-trough the plasma, contrary to what is commonly assumed in most theoretical models.

The non linear evolution of a magnetic island that rotates with angular velocity $\Omega = \omega/\omega_\phi$ relatively to the plasma angular velocity ω_ϕ, is described in Eq.(88-89) of[1]. When the island reaches a constant amplitude there is a solution for these equations in which Ω decays exponentially in time. The yellow line in #30026 Fig.1(f) is a non-linear least squares fit to the data with the function

$$\Omega(t) = \frac{f_{island}}{f_\phi} = 2.22 + 8.60 \times 10^5 e^{-\frac{t-63}{5.13}},$$

indicative of an exponentially decay in time.

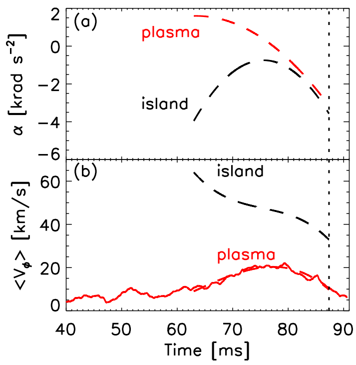

Figure 2: (a) Angular toroidal acceleration and (b) toroidal velocity for the period since the island saturates to disruption.

Conclusions

We have shown for the first time experimental evidence from TCABR high density plasmas, of synchronization between plasma and $2/1$ magnetic island natural toroidal angular acceleration, α, just before the disruption occurs. The data also indicates the island slips-trough the plasma, contrary to what is commonly assumed in most theoretical models.

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